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By Robert D. Ross

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RADIANT HEATING FOR MISSILE AND AIRCRAFT STRUCTURAL TESTING

By Robert D. Ross*

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INTRODUCTION

Ever since the first successful airplane was launched, the speed of flight has been pushed higher and higher. High speeds result in high rates of heat transfer to the skin of the airplane, thus creating the many problems frequently referred to as the "thermal thicket." The purpose of this paper is to discuss some of the equipment used in the experimental investigation of these problems, particularly the electric radiant heaters used to simulate the aerodynamic heat input to the aircraft or missile structure.

NATURE OF THE PROBLEM

The source of aerodynamic heating lies in the conversion of kinetic energy of the moving air into heat energy at the surface of the body. Except at the stagnation point, the heat input to the body can be expressed by the simple equation

$$q = h(T_{aw} - T_s) \quad (1)$$

where q is the heat input per unit area, h is the aerodynamic heat-transfer coefficient, and the term in parentheses is the temperature difference which produces the flow of heat. T_s is the temperature of the specimen surface, and T_{aw} is a quantity known as the adiabatic wall

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temperature, which may be called an effective temperature and can be computed from the equation

$$T_{aw} = T_a (1 + 0.2rM^2) \quad (2)$$

where T_a is the absolute ambient temperature, r the recovery factor, and M the Mach number.

Heat is lost from the surface of the structure in accordance with the Stefan-Boltzman law $q = kT_s^4$ where k is a quantity which includes the Stefan-Boltzman radiation constant and the emissivity of the surface. The net heat entering the structure will be the difference between the heat received and that lost at the surface, and is given by

$$q = h(T_{aw} - T_s) - kT_s^4 \quad (3)$$

In practice, however, k is not a constant, but varies somewhat as the surface temperature. To a sufficient approximation, k may be expressed as $(a + bT_s)$, where a and b are constants. Hence equation (3) becomes

$$q = h(T_{aw} - T_s) - (a + bT_s)T_s^4 \quad (4)$$

The problem, then, is to duplicate in the laboratory, with radiant heaters (or by other means), the variation with time of this net heat input to a given structure or structural component. At the time that aerodynamic heating first loomed as a serious problem, it was felt that surface heating rates of 50 Btu per square foot per second would suffice for a considerable period of time. However, progress in the realm of hypersonic and space (orbital) flight have brought the threshold of

heating rates to much higher values with attendant surface temperatures in excess of 3,000° R. A brief indication of the progress made in attempting to reach these high values will now be given.

HEATING METHODS

One early scheme proposed for producing high heating rates consisted of heating a refractory wall in a furnace to 3,500° R and then swinging the wall out of the furnace to a position in front of the test specimen. The wall would then heat the specimen by radiation. This method was discarded as being too cumbersome and inflexible, and attention was turned to infrared heat lamps.

Another device consisted of an array of R-40 type lamps. These lamps contained a 375-watt filament in a $3\frac{1}{2}$ -inch-diameter glass bulb. On the basis of watts per square inch of gross area, these lamps would not produce nearly the desired heating rate. However, at rated voltage the filament temperature was relatively low, thus allowing increased voltage to be applied without destroying the filament. Although of no surprise to lamp engineers, it was found that 280 volts or more could be applied to a 115-volt lamp, so that the power radiated was 1,500 watts. It appeared that this would be a useful amount of power per lamp, accordingly several lamps were assembled into an array, packed as closely together as physically possible. The arrangement is shown in figure 1. This radiator was capable of producing heating rates of about 15 Btu per square foot per second in a specimen 2 inches away. However, the

arrangement was not satisfactory, because in addition to having insufficient output, the lamps tended to explode after about 30 seconds, or the solder in the base of the lamp would melt and short-circuit the socket.

About this time an electrical manufacturer was in the process of developing a lamp with a straight filament sealed in a 3/8-inch-diameter quartz tube, and a few preliminary models of the lamps were obtained. When assembled into an array, the lamps gave heating rates of useful magnitudes. These lamps rapidly became commercially available in quantity, and further development has resulted in the present quartz lamps.

The quartz lamps are available in lighted lengths of 10, 25, and 50 inches, all rated at 100 watts and approximately 20 volts per inch of length. However, to realize their full power capabilities the lamps are operated at twice their rated voltage, or 460, 1,150, and 2,300 volts for the respective lengths. At double voltage the power goes up by a factor of 3, giving 3, $7\frac{1}{2}$, and 15 kilowatts for the three lengths. The lamps are also manufactured with a filament of twice the power dissipation in 10- and 25-inch lengths, so that 6 and 15 kilowatts, respectively, per lamp are obtained. The power for values of voltage other than rated is given in figure 2.

Lamps such as these give the designer considerable flexibility in his choice of radiators and test specimens. The work at the NASA involves a wide range of shapes and sizes of specimens, resulting in the design of a radiator to suit each application. The radiators are of very simple

design, and consist of two bus bars with the lamps supported between them by the lead wires, or pigtails. The busses may be slotted where more accurate positioning of lamps is desired. Figure 3 shows a pair of general purpose radiators each made up of ninety-two 10-inch lamps. Each radiator is operated at up to 460 volts and at power ratings up to 275 kilowatts. The lamps are stacked in two layers or decks thus doubling the number of lamps in a given area and resulting in higher heating rates. A reflector (not visible in the figure) made of 1/4-inch-thick polished aluminum is placed behind each double deck of lamps.

A radiator such as this is, of course, not suitable for continuous duty; it may be operated continuously for only about 15 seconds, after which lamp failures begin to occur. Also, the reflector may melt if the running time is appreciably greater than 15 seconds.

Lamps may fail in one of several ways. When operated in a closely packed radiator, such as shown in the figure, about 5 percent of the lamps will be blackened and distorted after 20 seconds of continuous usage. The quartz envelope blackens first so that it absorbs radiated heat; this softens the quartz and thus causes it to distort. The failures are progressive; after 20 runs perhaps half of the lamps will have failed. Less frequently failures may be caused either by buckling of the filament so that it melts through the quartz tube, or by a faulty seal which results in an air leak. When the lamps are operated at lower temperatures for longer times, the chief cause of failure is by a clouding of the quartz, which results in an increase in lamp temperature but in a decrease in available radiation.

It must be understood, however, that all the foregoing failures apply when the lamps are employed in closely packed groups and operated at excessive voltages. A single lamp operated at rated voltage will last many hours and for 24 hours or more at 200 percent voltage. Also, a single lamp has been operated at 200 percent voltage in an ambient temperature of 900° F for one minute with no signs of distress.

TYPICAL RADIATORS

The simple design of the quartz tube lamps makes them readily adaptable to assembly in radiators of various shapes. Examples of the more frequently used designs will now be given. Figure 4 shows a radiator for heating a cylindrical model. The radiator consists of 225 25-inch lamps, connected for 3-phase operation. A cylindrical reflector is placed around the whole assembly. The busses at the ends are brass strips bent to the proper radius, with a small insulating block of asbestos cement to insulate between the phases. The lamps were fastened to the busses by their own pigtails.

Figure 5 illustrates the ease with which a radiator can be assembled and tailored to a specific specimen. The specimen is a delta wing, with the lamps supported on a simple bus structure above it. The busses are made of sheet aluminum and the lamps again are hung by their pigtails. The busses are all insulated from each other, and the lamps connected in three independent groups.

Wing specimens are frequently heated nonuniformly, with most of the heat concentrated on the leading edge, as would occur in flight. This presents something of a problem in the radiator design for the case of a delta wing such as shown in the figure. The problem may be solved, partially at least, by a variation in the surface treatment of the specimen. In this case, the leading edge was finished dull black to increase its absorptivity, then a zone of grey paint, and finally a bright aluminum paint was applied.

Figure 6 shows a radiator used to heat a trapezoidal wing section. As before, the lamps were connected in three independent groups. There was a hinge between the ends of adjacent groups of lamps so as to enable the assembly to follow approximately the deformation of the wing. It was necessary to assemble this radiator in a hurry, so time was not taken to drill the busses for screws to hold the lamp pigtails. The pigtails were merely wrapped around the busses and held in place with clamp-type paper clips.

One other radiator of interest is shown in figure 7. Here the assignment was to heat a graphite tube to a very high temperature and then to maintain that temperature. To do this, it was necessary to cool the reflector and the lamps. The water-cooled reflector encircled the lamps (as shown in the fig.), while the lamps and end connections were cooled by jets of air issuing from the circular manifolds. Because this air would also cool the specimen, a tube of Vycor glass, placed between the specimen and lamps, was used as a shield. This shield allowed

the radiant energy to fall on the specimen and at the same time protected the graphite tube from the air blast. With this furnace, a specimen temperature of $3,600^{\circ}$ R was attained and held for thirty minutes.

RADIATOR DESIGN

The design of radiators for a specific application is largely empirical. Exact theoretical designs can be worked out, but there are so many unknown parameters to be measured in each case that it is usually simpler to build the radiator and then measure its performance. As an example of such measurements, figure 8 shows how the heating capacity of a radiator equipped with reflectors varies as the distance between specimen and lamps is varied. It should be noted that the radiation does not decrease as the inverse square of the distance, since the radiation does not originate from a point source. The curves shown apply to the energy received at the center of the specimen with a radiator 10 by 12 inches in size.

Due to geometrical factors involved in the radiant interchange between two objects, the received energy over the face of a specimen in front of a finite radiator is not uniform, but decreases as the distance from the center increases. Typical experimental curves are shown in figure 9. These curves are similar to contours on a map; along any given curve the received energy is a constant. The curves were taken over the surface of a specimen 9 by 18 inches in size placed 4 inches away from a 10- by 20-inch radiator. From these curves, it may be seen

that if a 10-percent reduction in heating is permissible between the center and the edges of a specimen, the linear dimensions of the radiator must be about $1\frac{1}{2}$ times those of the specimen. On the other hand, if no more than a 5-percent variation can be tolerated, the radiator should be at least twice as big. In cases where it is practical to include reflectors around the side of the radiator and specimen the reduction at the edges will be considerably less.

Frequently groups of lamps must be operated end-to-end in order to extend the size of a radiator. When this is done there will be a decrease in received energy in front of the point where the lamp ends are joined together. This can be compensated for by placing extra lamps transversely in the gap, as pictured in figure 10. The effect of these lamps is shown in figure 11, from which it may be seen that a nearly flat heating rate may be obtained if the proper specimen distance is employed.

Figure 12 shows the overall efficiency, or the ratio of the energy received at the center of a specimen to the energy input to the radiator, on a unit area basis. The efficiency decreases as the specimen distance is increased. The curves also show the loss in efficiency when the reflector is omitted, as occurs on occasions such as on long-time tests where melting of the reflector, if not force-cooled, would otherwise result.

Figure 13 shows the power input necessary to hold a flat-plate specimen at a given temperature; with the specimen placed 2 inches in

front of the radiator. The plate was 0.062-inch-thick steel, and was free to radiate from the back side.

RADIATOR CONTROL

In order to simulate the time variation of aerodynamic heating conditions as expressed by equation (4), some form of continuous voltage control is desirable. The most frequently used types are saturable reactors and Ignitron controllers. Because of their high speed of response and adaptability to a wide range of connected loads, Ignitrons are used at the NASA. The controller, when used in conjunction with a programed-input computer, makes a very flexible system for simulated aerodynamic heating.

A block diagram of the electrical control system is shown in figure 14. By operating changeover switches, either heating rate or specimen temperature may be programed against time. Also, the adiabatic wall temperature and heat-transfer coefficient may be programed and the system operated in accordance with the heat-transfer equation given previously (eq. (4)). When the system is operated in this manner, the desired values of T_{aw} and h versus time are placed on the two function generators. The specimen temperature T_s is sensed by a thermocouple, amplified, and subtracted from T_{aw} in a difference amplifier. The resulting output is then multiplied by the transfer coefficient h coming from the function generator, and the quantity $h(T_{aw} - T_s)$ fed into a second difference amplifier. The other input to this second

amplifier is the radiation loss term $(a + bT_s)T_s^4$ which is obtained from the thermocouple signal and the constants a and b which were preset into the network. The output of this amplifier then represents the left-hand side of the heat balance equation which is fed into the error amplifier. This is the desired quantity; the actual quantity of heat fed to the specimen is measured and supplied to the error amplifier, and the difference between the two is used to control the Ignitrons. The Ignitrons operate to reduce the error to as near zero as possible, consistent with system stability and speed of response.

With this system, the heat input to the specimen is not measured directly, but is taken as proportional to the power input to the lamps. The efficiency or constant of proportionality has to be measured for each case and is regarded as constant over the range of temperatures used in any one test. One method of measuring the efficiency is to measure the power supplied to the lamps and at the same time measure the rate of temperature rise on a dummy specimen of known thermal characteristics.

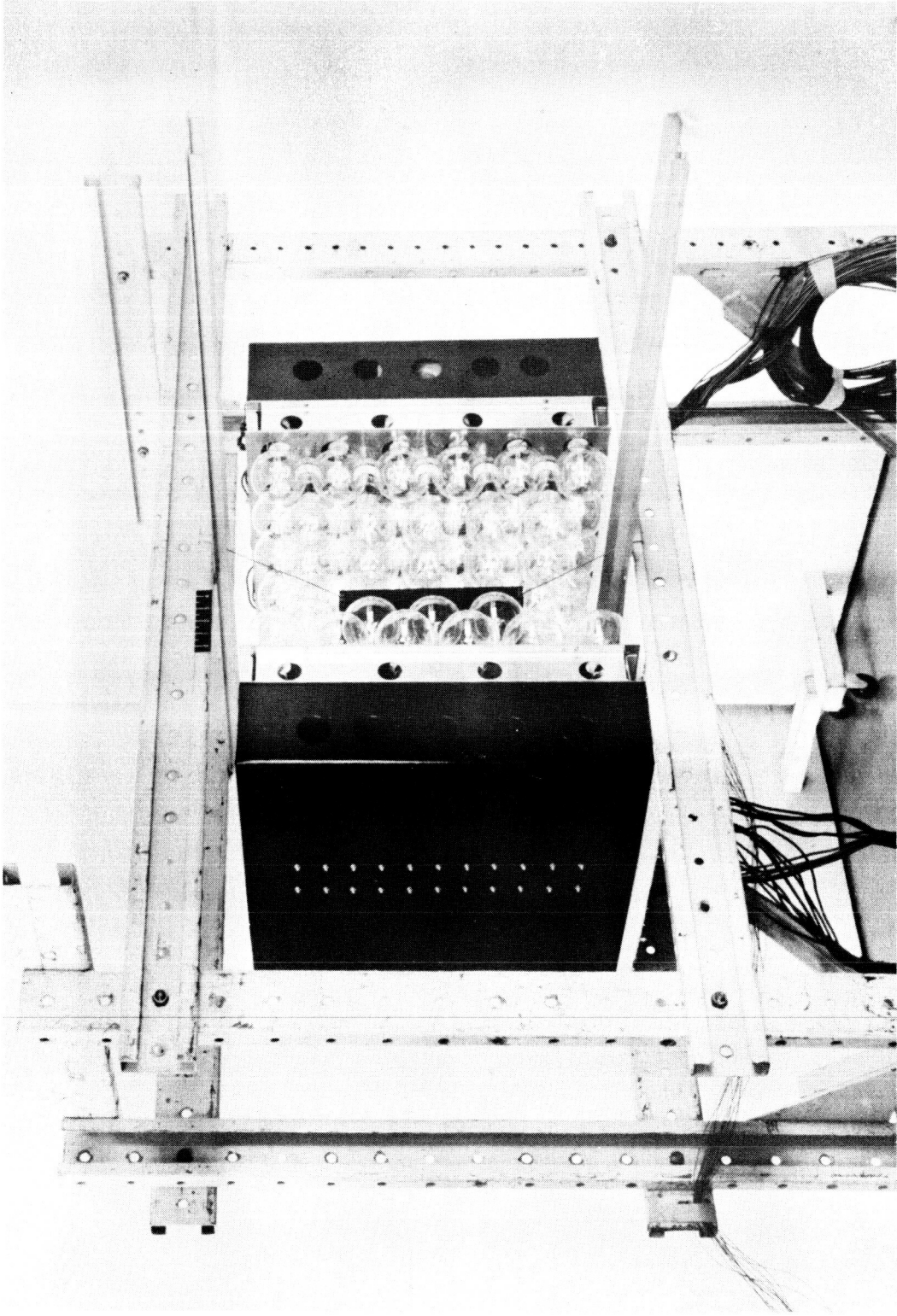
Another method of measuring heat input to the specimen is to measure the rate of change of the specimen temperature; this, when combined with the physical constants of the material, gives the heat input. The computer shown in the figure is set up so that temperature rate feedback may be incorporated at a future date.

CONCLUDING REMARKS

Quartz tube heat lamps, used with a suitable power controller and analog computer, make a versatile tool for simulating the effects of aerodynamic heating. Heating rates up to about 100 Btu per square foot per second have been obtained with the standard lamp of 100 watts per inch rating and rates of about 60 percent greater than this value with lamps of 200 watts per inch rating. Variable voltage control systems have been developed which enable a time variation of the heat in accordance with a preselected schedule. However, the demand for even higher rates of heating continues so that there remains much opportunity for the development of lamps and radiators capable of still greater radiating capacity.

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Figure 1.- Early type radiator assembled from R-40 lamps. L-76644

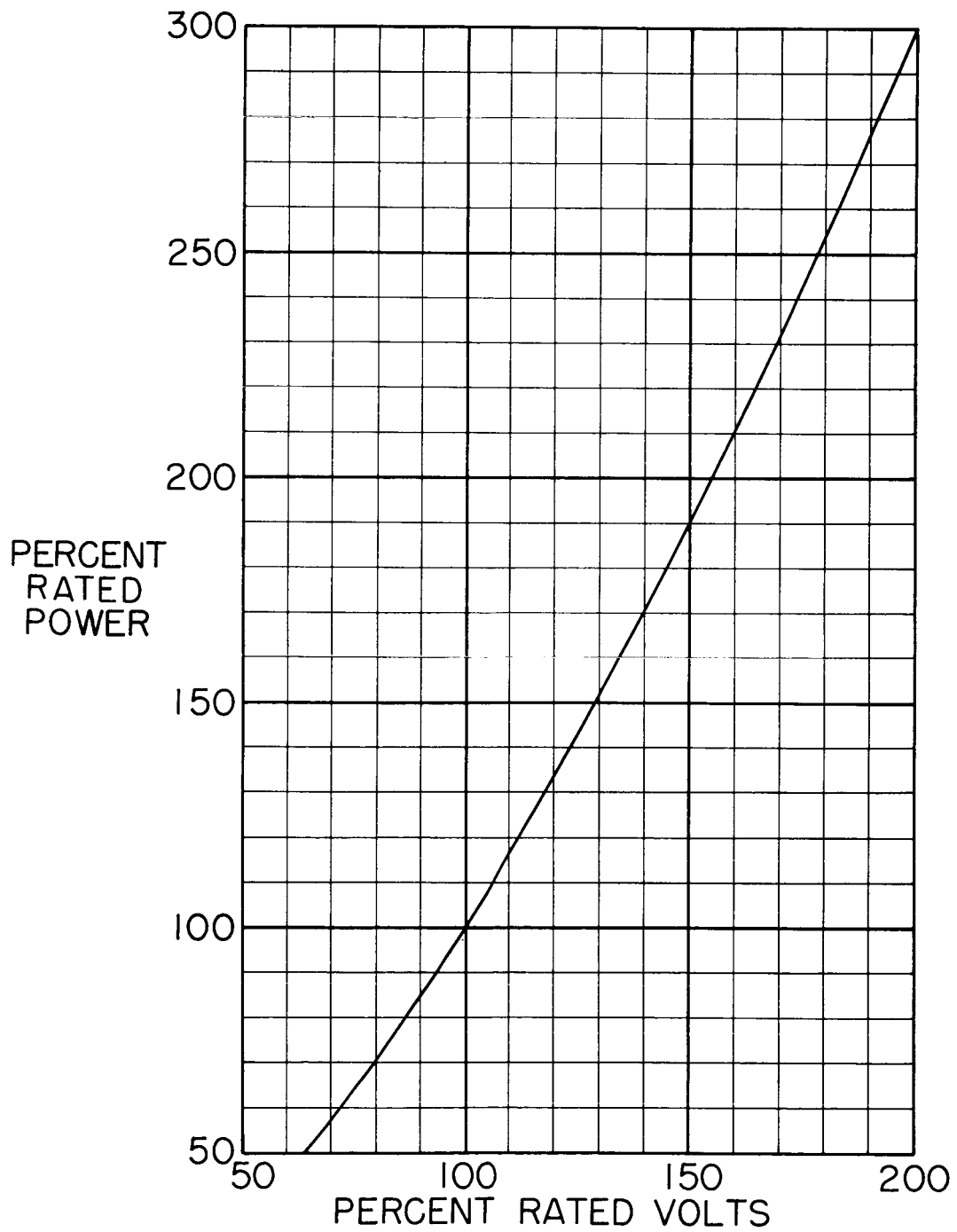
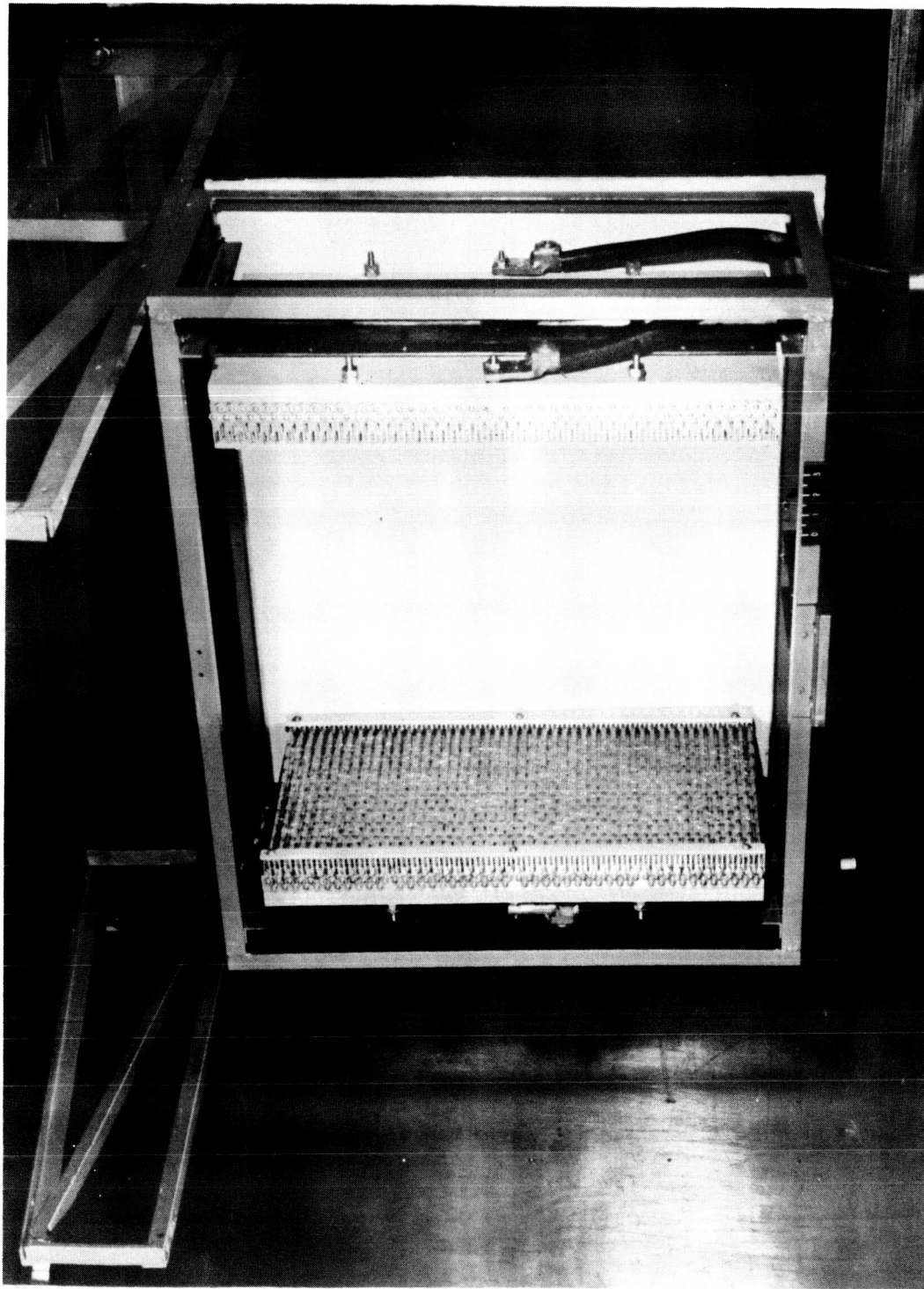
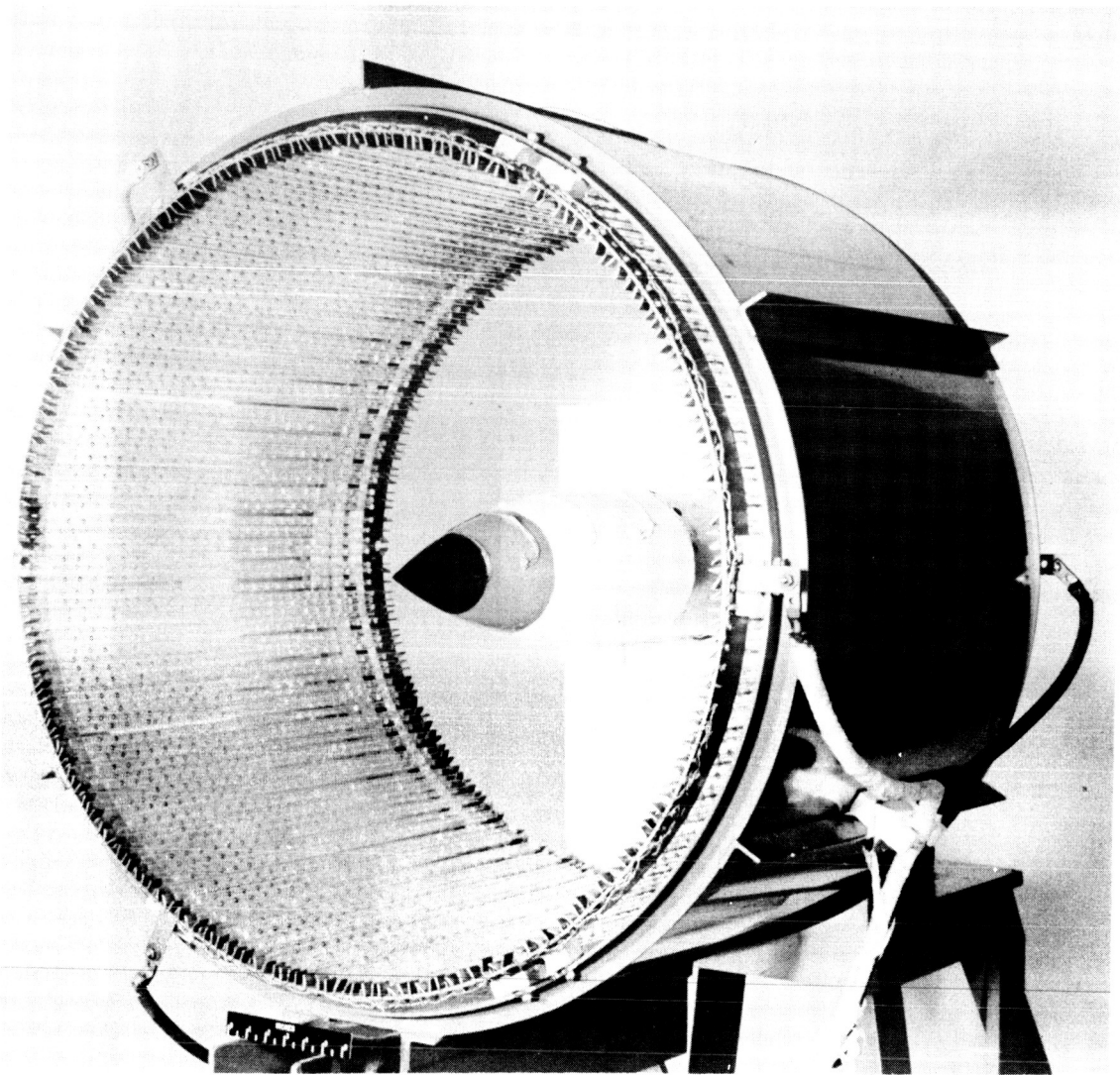


Figure 2.- Generalized power-voltage relation for T-3 quartz lamps. NASA



NASA
Figure 3.- General purpose flat radiator. L-87632



NASA

Figure 4.- Large cylindrical radiator. L-57-3123

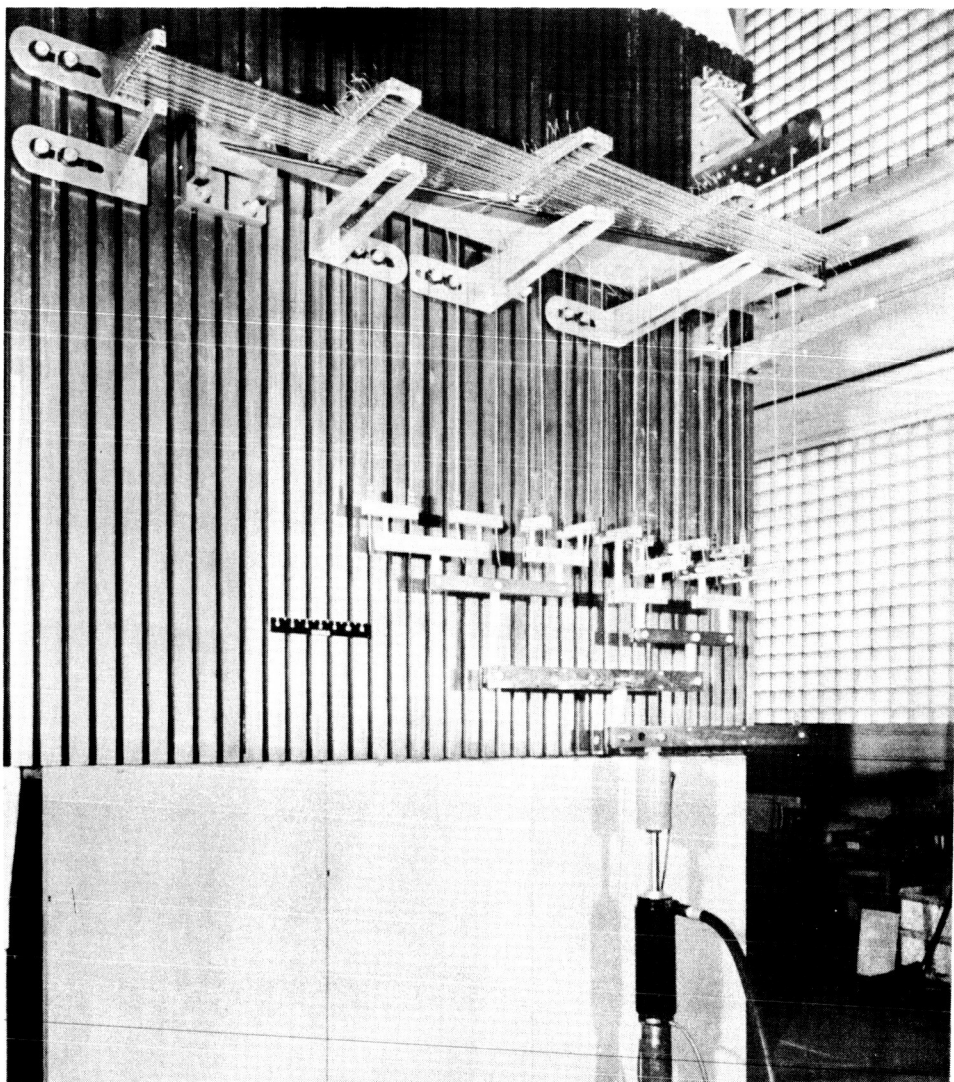
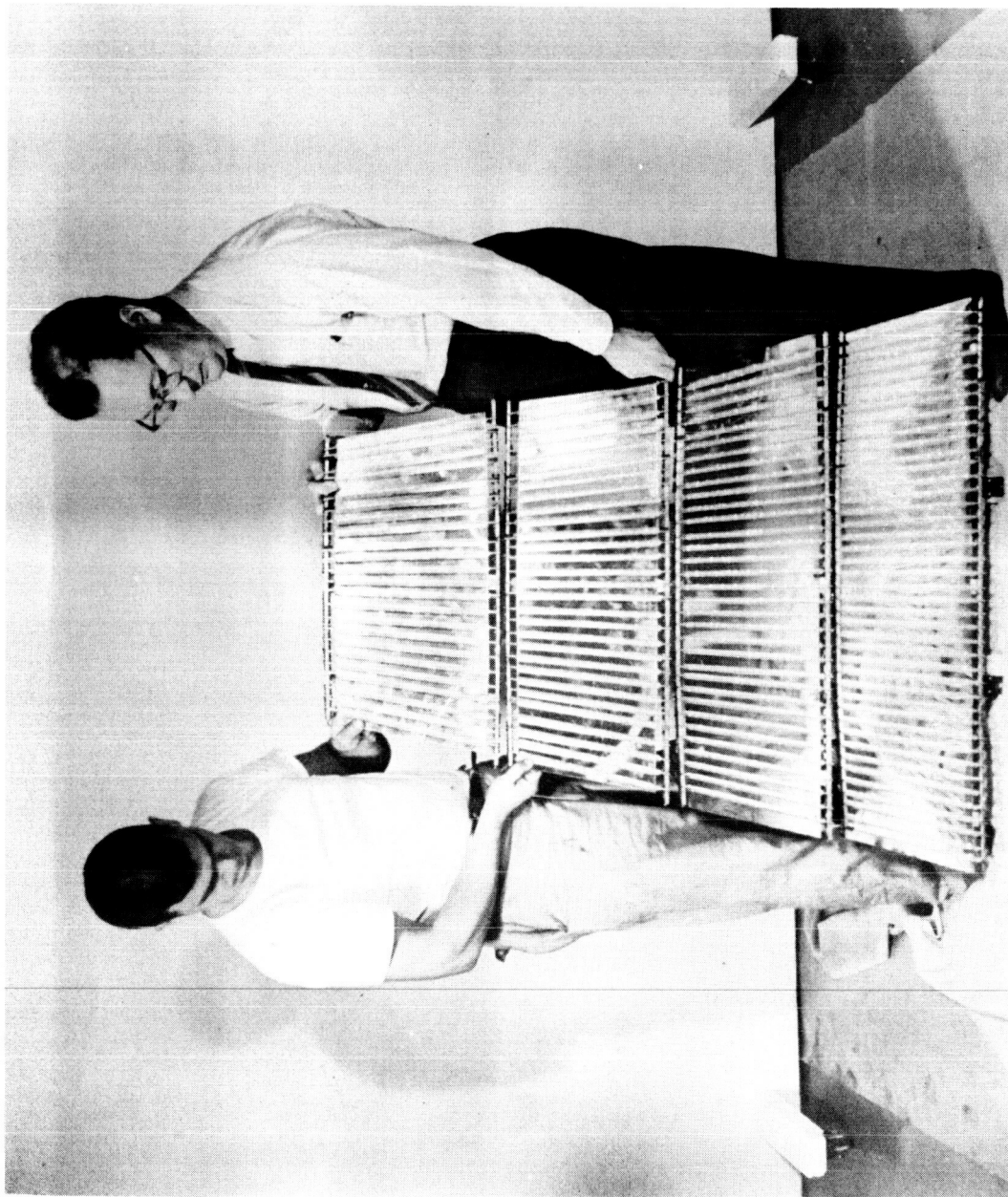
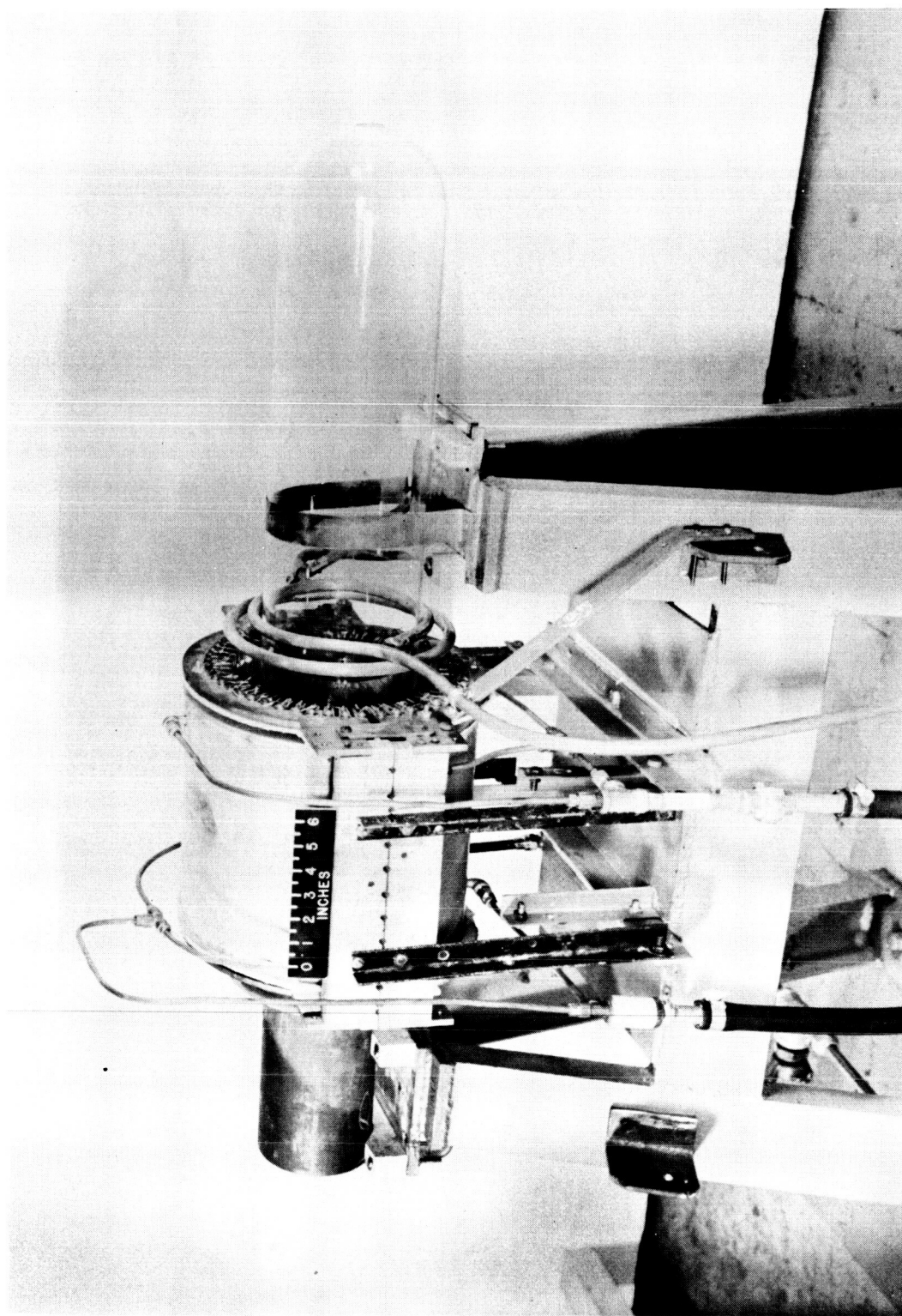


Figure 5.- Radiator and loading device for delta wing. NASA L-90756



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L-95542
Figure 6.- Articulated radiator for rectangular wing.



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Figure 7.-- High intensity cylindrical radiator with forced cooling. L-58-3543

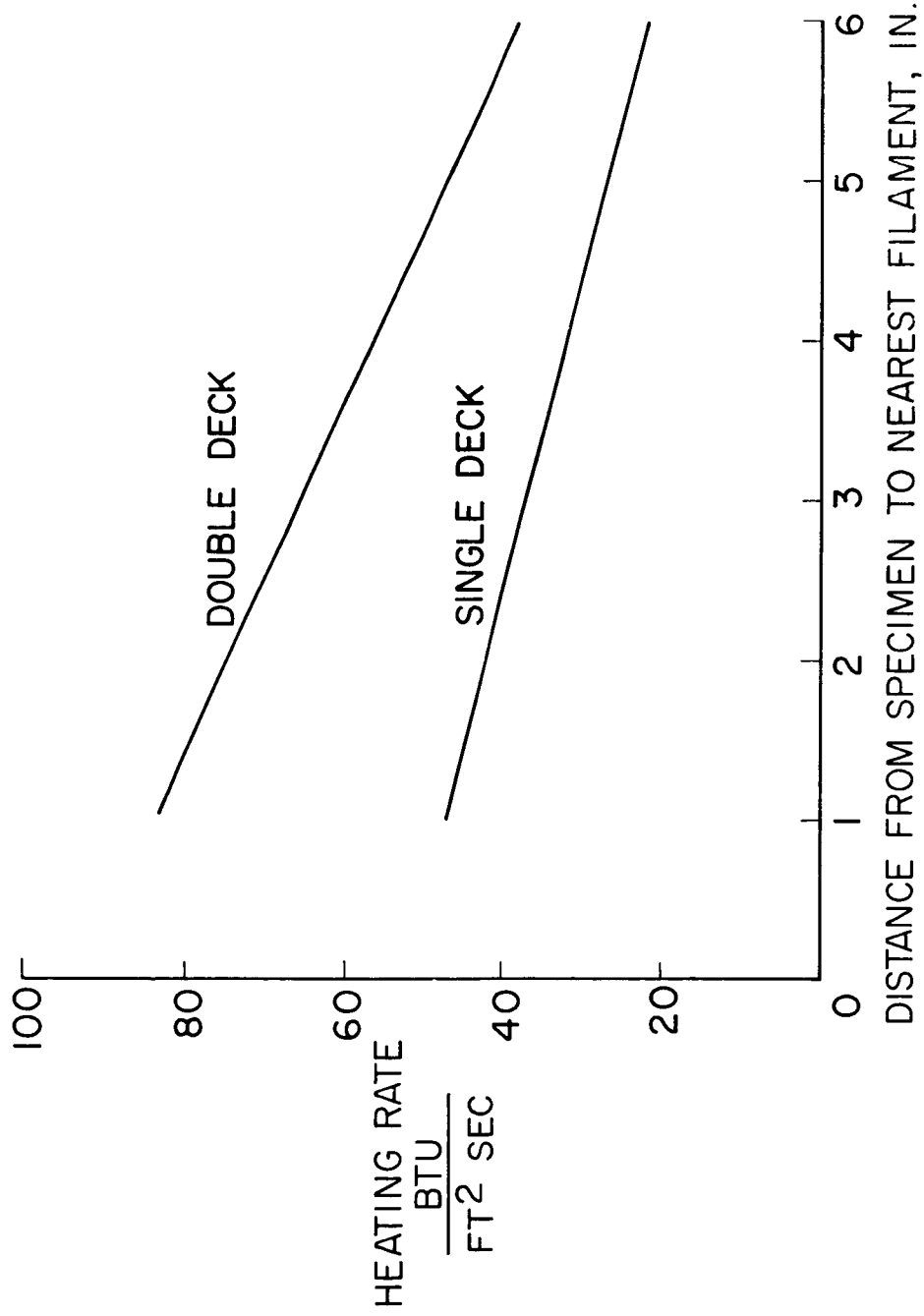


Figure 8.- Heating rates obtained from 10- by 12-inch radiator with NASA 1,000-watt; 10-inch lamps at 460 volts.

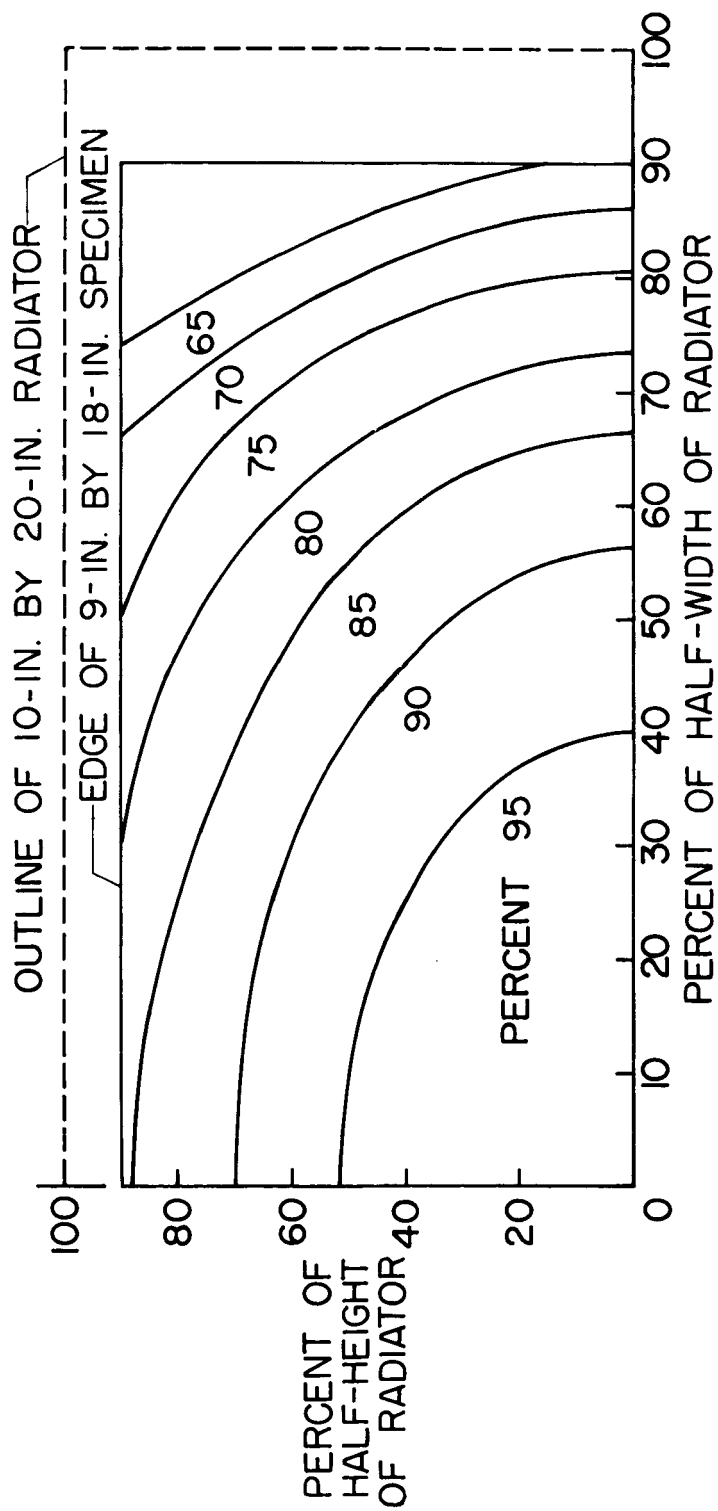
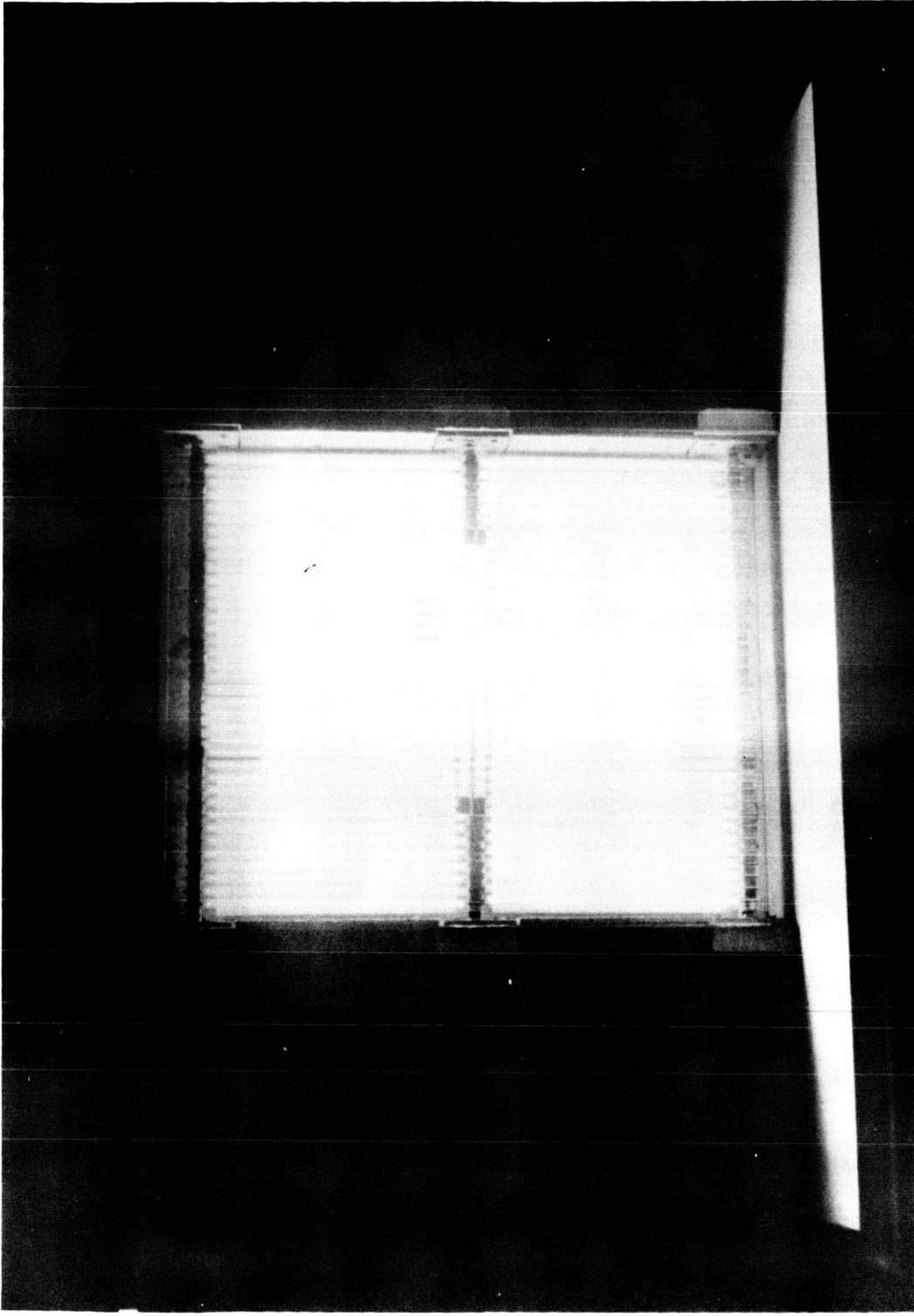


Figure 9.- Heating rate contours for plane plate before plane radiator. NASA



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Figure 10.- Radiator with transverse lamps in dead space. L-87237

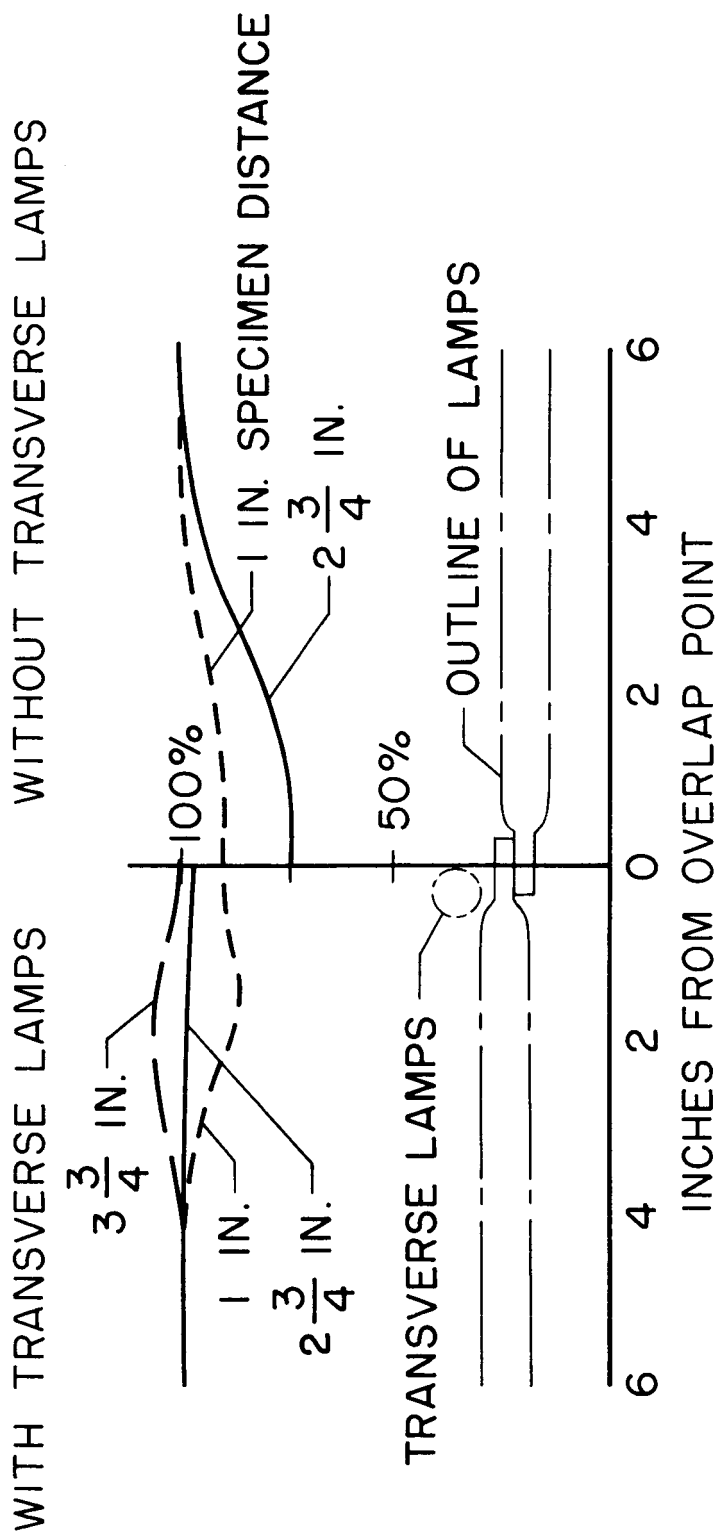


Figure 11.- Variation of heating effect due to overlap at end of lamps; NASA percent of heating 6 inches from lap.

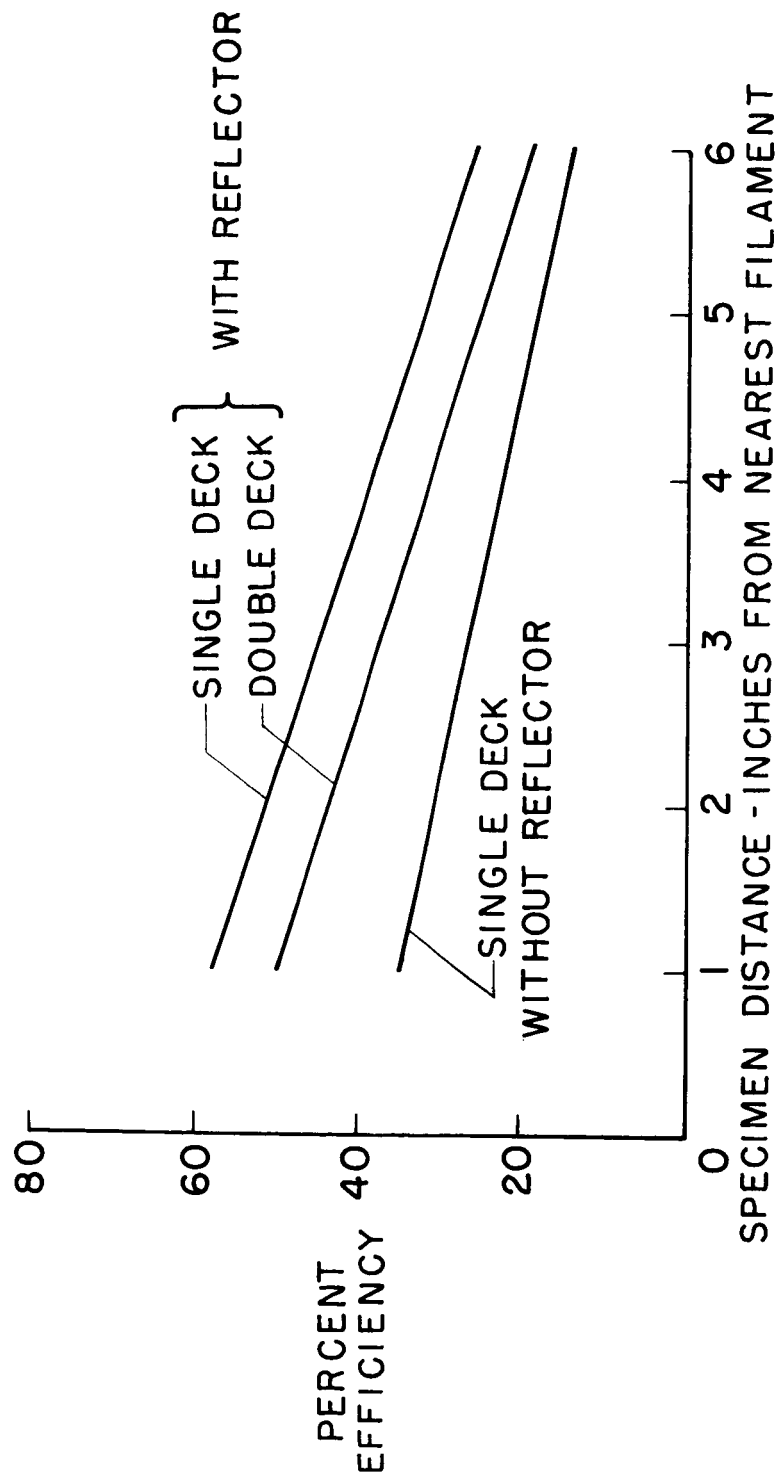


Figure 12.- Overall efficiency of radiator unit. NASA

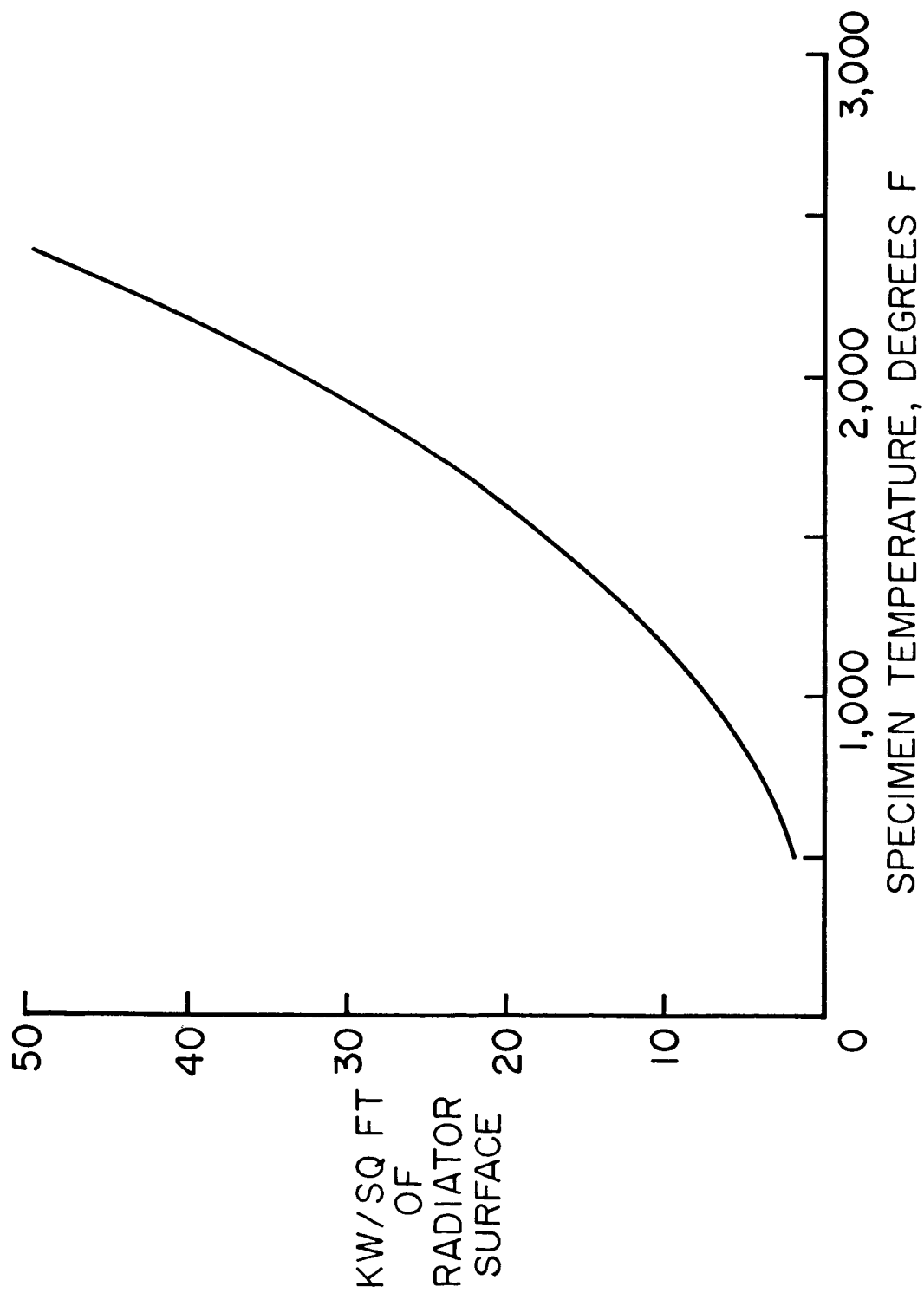


Figure 13.- Power required to maintain temperature of a specimen at NASA
2 inches from lamps.

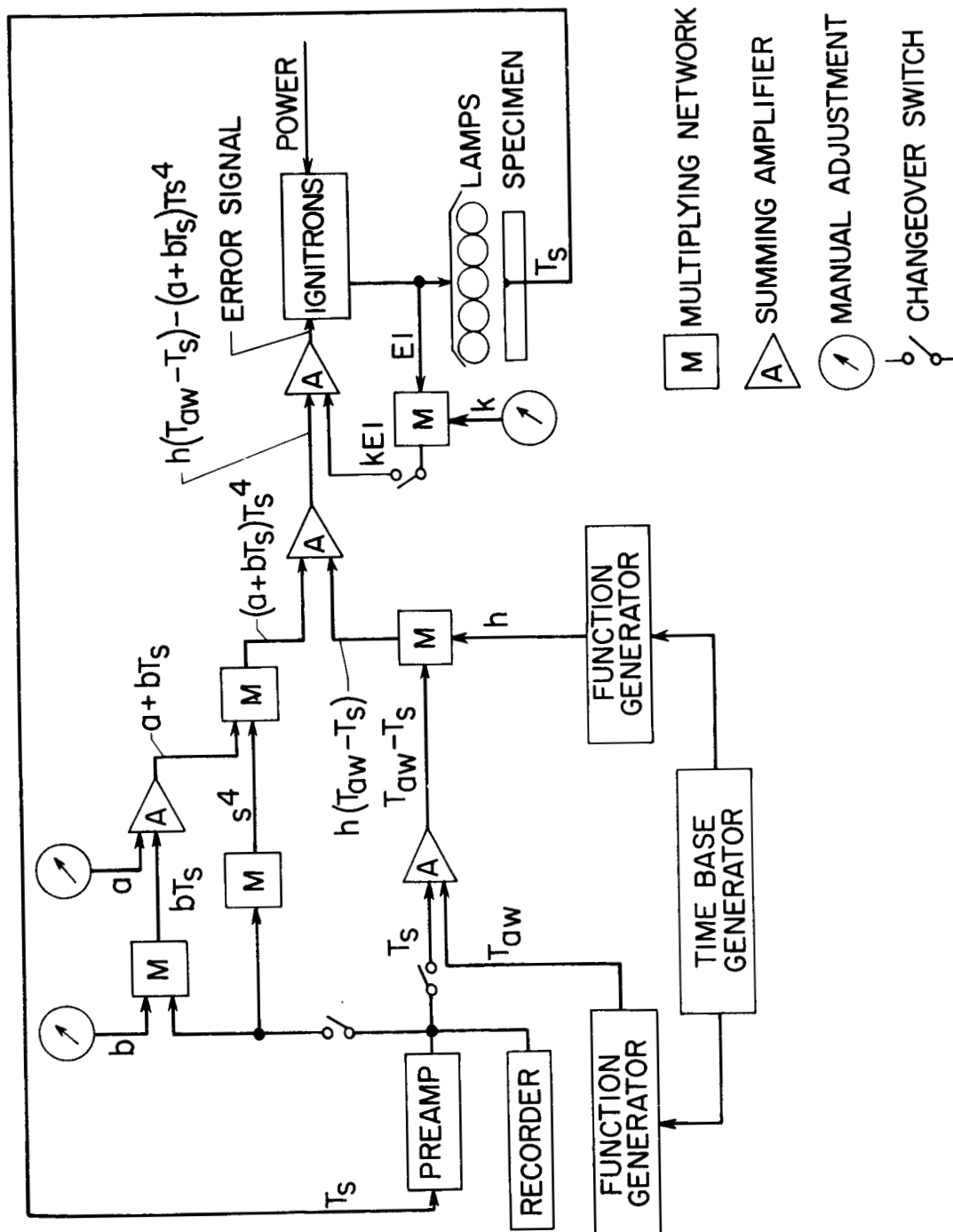


Figure 14.- Block diagram of computer. NASA